Confirmation and Analysis of Circular Polarization from Sagittarius A*

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ABSTRACT

Recently Bower et al. (1999b) have reported the detection of circular polarization from the Galactic Center black hole candidate, Sagittarius A*. We provide an independent confirmation of this detection, and provide some analysis on the possible mechanisms.

Subject headings: Galaxy: center – polarization – radiation mechanisms: non-thermal – scattering

1. Introduction

The flat-spectrum, compact radio source in the Galactic Center, Sagittarius A* (Sgr A*), has long been believed to mark a massive black hole at the dynamical center of the Galaxy (Lynden-Bell & Rees 1971). Eckart & Genzel (1996,1997) and Ghez et al. (1998) provide compelling evidence that there is a dark mass of $\approx 2.6 \times 10^6\, M_\odot$ coincident with Sgr A*. Furthermore VLBI observations suggest the intrinsic size of Sgr A* is no larger than 1 to 3.6 AU (Krichbaum et al. 1998; Lo et al. 1998; Rogers et al. 1994; Bower & Backer 1998). The observed size, however, is substantially larger as a result of scattering by interstellar electrons in the vicinity of Sgr A* (Davies, Walsh & Booth 1976), and follows a λ^2 dependence.

If Sgr A* is a synchrotron source, polarized emission may be be expected, and would prove a tight constraint on some of the proposed models. However, despite numerous attempts, linear polarization has not been detected from Sgr A* (e.g. Bower et al., 1999a). This is so even at high frequencies, or with experiments which should be sensitive to linear polarization with high Faraday rotation measures (Bower et al. are sensitive to limits of RM $= 10^7$ rad m^{-2}).

Recently Bower et al. (1999b) have reported the detection of circular polarization from Sgr A* at 4.8 and 8.4 GHz. We report an independent confirmation of this detection at 4.8 GHz using the Australia Telescope Compact Array (ATCA). We note that we have used a different telescope, calibrators and calibration procedures and software to Bower et al.

Care is needed in analysing radio astronomy data for circular polarization, particularly given that the observed level of circular polarization in synchrotron sources is always small. A minor error in the polarimetric calibration can allow a fraction of total intensity to masquerade as circular polarization. Such a miscalibration will lead to an erroneous image which has no obvious error artifacts. This is unlike observations of linear polarization

with alt-az antennas (small miscalibration will lead to artifacts, rather than an apparently clean image). The VLA's off-axis design and circularly-polarized feeds also make it a poor instrument for circular polarization measurements. Given these caveats, and the general mixed history of the detection of circular polarization, we believe an independent confirmation adds significant weight to the detection of Bower et al.

2. Observations and Results

We have made one new observation and used two archival observations from the ATCA to independently test the detection of Bower et al. The ATCA is a radio interferometer situated in eastern Australia at a latitude of $-30°$. It consists of 6 antennas over a 6 km baseline. With an on-axis feed design, dual linear polarimetric measurements and alt-az antenna mounts, it is an excellent instrument for the measurement of circular polarization. Three observations, made in March 1996, 1997 and 1999, were analysed. The observations were 12 h, 8 h and 6 h in length, respectively. These observations used a variety of bandwidths, array configurations and correlator settings, but were all made at 4.8 GHz. All runs included observations of the blazar PKS B1730-130 approximately once every 30 min and included at least one observation of the ATCA's primary flux calibrator, PKS B1934-638. With the ATCA having linearly polarized feeds, the most important calibration step is in determining the antenna polarization leakage terms (the so-called "D terms"). This was done using the PKS B1934-638 data, which we have assumed to have Stokes parameters of $(I, Q, U, V) = (5.829, 0, 0, 1.5 \times 10^{-3})$ Jy. PKS B1934-638 is a GHz peaked spectrum source. Numerous ATCA and Parkes observations have failed to detect linear polarization from it (even with appreciable rotation measure). However work by Komesaroff el al. (1984) and Rayner et al. (submitted to MNRAS) suggest some weak circular polarization. The value we adopt is from Rayner et al. From the data for

PKS B1730-130, we have performed a simultaneous solution for antenna gains as a function of time and source polarization (note that PKS B1730-130 is known to be time-variable and circularly polarized at the level of several milliJanskys). The reduced PKS B1730-130 data was consistent with a time-variable polarized point source.

In the polarimetric calibration process, we have included a subtle geometric correction as follows. Nominally, the geometry of the axes of all the ATCA antennas is identical. In reality, of course, this is not the case, and the deviation from the nominal axis geometry, which is typically of order $1'$, is determined in an antenna pointing solution. For high precision work using alt-az antennas (such as the ATCA antennas) on sources that transit near the zenith, the true antenna geometry needs to be used in the calculation of parallactic angle (Sault et al, 1991; Kesteven 1997). With the declination of Sgr A* ($\delta = -29°$) differing from the ATCA's latitude by only 1°, this is a detectable effect.

The minimum spacing used in the analysis was 50 kλ in total intensity and 5 kλ in circular polarization. The total intensity limit is to avoid confusion from the extended emission in the Galactic Center. In circular polarization, the only emission is from Sgr A*, and so confusion is not an issue. However the use of a minimum baseline for circular polarization excludes possible contamination from leakage of the rapidly rising total intensity emission at short spacings. This would be caused by small residual polarization calibration errors. Table 1 summarizes the results of our observations. We give the total intensity, circular polarization and fractional circular polarization of Sgr A*. We also give the RMS residual in the Stokes V image and σ_{V} (the theoretical noise in the Stokes-V image which would result from the measured receiver noise). The results show good self-consistency, and agree well with the VLA detection of -2.0 mJy.

EDITOR: PLACE TABLE 1 HERE.

3. Discussion

The circular polarization properties of Sgr A* are broadly consistent with those found in the cores of extragalactic radio sources. The 0.3 – 0.4% circular polarization of Sgr A* is toward the high end of the range – typical values for extragalactic objects are 0.05 to 0.5 % (e.g. Roberts et al. 1975, de Pater & Weiler 1982 and Weiler & de Pater 1983). The absence of linear polarization is, however, unusual.

Variations in the circularly polarized flux indicate either a change in the intrinsic degree of circular polarization or that the circularly polarized source is small enough to exhibit the effects of interstellar scintillation. Since the circular polarization in extragalactic sources is sometimes found to be variable (Komesaroff et al. 1984) and the total intensity of Sgr A* is itself variable (e.g. Brown & Lo 1982), it is of interest to place even a crude constraint on the degree of variability of the circular polarization. Although obviously hampered by the small number of measurements, we note the possibility that the circularly polarized component is variable. The normalized variance of the total intensity, defined by $\langle[I-\bar{I}]^2\rangle/\bar{I}^2$, is 0.11. The corresponding quantity for the circular polarization is 0.16, however at least 0.09 (60%) of this may be attributed to measurement uncertainty.

The degree of circular polarization (V/I) may also vary. Variation in this quantity implies that either the intrinsic circular polarization is variable or, if the source scintillates, that the polarized emission experiences different phase fluctuations along its ray path compared to the bulk of the (unpolarized) emission. We can place a constraint on the variability of the degree of circular polarization: the 3σ upper limit $\Delta(V/I)/[\bar{V}/\bar{I}]$, is $\approx 25\%$. This number is only relevant to the variations on the timescale comparable to our observing intervals (i.e. one year).

4. Origin of the Circular Polarization

It is of considerable interest to consider the physical properties of Sgr A* which give rise to the observed circular polarization. It is possible that the circular polarization is intrinsic to the synchrotron emission (Legg & Westfold 1968), or it may result from one of several propagation-related mechanisms: 'circular repolarization' converts linear to circular polarization and may occur either in a cold plasma (Pacholczyk 1973), or in an electron-positron pair dominated plasma (Sazonov 1969, Jones & O'Dell 1977a,b). Circular polarization may also be induced by scintillation (Macquart & Melrose 1999).

It is possible that the circular polarization is associated with only a small component of the total flux density of Sgr A*. In the following discussion we therefore denote the degree of circular polarization as $m_c = 0.0035\,\xi$, where $\xi \geq 1$.

The circular polarization due to sychrotron radiation from a power law distribution of relativistic electrons $N(\epsilon) \propto \epsilon^{-2\alpha-1}$ is (Melrose 1971)

$$m_c = \frac{\cot\theta}{3}\left(\frac{\nu}{3\,\nu_H \sin\theta}\right)^{-1/2} f(\alpha), \tag{1}$$

where θ is the angle between the line of sight, ν is in hertz and $\nu_H = 2.8 \times 10^6 B$ Hz is the electron gyrofrequency, where B is the magnetic field in gauss. The function $f(\alpha)$ is a weak function of the spectral index, α; for optically thick emission in the limit of strong Faraday rotation $f(\alpha)$ only varies monotonically between 0.6 and 2.0 for α between 0 and 2 (see Melrose 1971). The observed flux density of Sgr A* increases with frequency up to at least 850 GHz (Falcke et al. 1998, Serabyn et al. 1997) and is roughly proportional to $\nu^{1/3}$, suggesting that the source is optically thick at $\nu = 4.8$ GHz. The high magnetic fields and particle densities thought to occur to occur in the source (e.g. Beckert et al. 1996) motivates the use of the strong Faraday rotation limit. The high RM measurements (e.g., Yusef-Zadeh, Wardle & Parastaran 1997) in the vicinity of Sgr A* support the

use of the strong Faraday rotation limit. (The strong Faraday rotation limit does not necessarily imply linear depolarization and is applicable whenever negligible absorption occurs over a path length in which the plane of linear polarization rotates through 2 π radians.) The electron energy spectrum is uncertain due to the combination of factors that influence the flux density in the region in which spectral turnover occurs. Taking $\alpha = 0$, the circular polarization may be explained in terms of synchrotron emission from a magnetic field $B = 0.19\,\xi^2\,|\sec\theta\tan\theta|$ G, while for $\alpha = 2$, the implied magnetic field is $B = 0.015\,\xi^2\,|\sec\theta\tan\theta|$ G. For $\alpha = 0$ this is equivalent to generation of circular polarization from electrons with an effective Lorentz factor $\gamma = |\cot\theta| f(\alpha)/3m_c = 54.7|\cot\theta|\,\xi^{-1}$. Below the self-absorption turnover frequency one has $T_b \approx 3.3 \times 10^{11}\,\xi^{-1}|\cot\theta|$ K, which is near the inverse Compton limit for $\xi^{-1}|\cot\theta| \sim 1$. Assuming a flux density of $640\xi^{-1}$ mJy for the circularly polarized component (see Table 1), this brightness temperature implies an angular size of $0.19\,(\cot\theta)^{-1/2}$ mas (1.7 AU at 8.5 kpc) at 4.8 GHz. For $\alpha = 2$ one has $\gamma = 193|\cot\theta|\,\xi^{-1}$, $T_b \approx 1.1 \times 10^{12}\,\xi^{-1}|\cot\theta|$ K, and an angular size of $0.10\,(\cot\theta)^{-1/2}$ mas. Note that both estimates of the angular size are comparable to the intrinsic size of Sgr A* determined by Lo et al. (1998) at λ7 mm. It therefore appears viable to explain the magnitude of the circular polarization in terms of that intrinsic to synchrotron emission.

The presence of a relativistic pair plasma has been suggested as the cause of circular polarization of a compact component of 3C 279 (Wardle et al. 1998). It is therefore relevant to consider the contribution of such a plasma to the observed properties of the circular polarization in Sgr A*.

In a plasma dominated by relativistic pairs the natural modes of the plasma are linearly polarized. Propagation through such a medium causes Stokes U to cycle into V. Assuming $V_{\rm intrinsic} = 0$, and denoting the degree of linear polarization as m_l, propagation through a

homogeneous medium gives rise to circular polarization as follows:

$$m_c = m_l \sin\psi \sin\lambda^3 \mathrm{RRM}, \tag{2}$$

where ψ is the sky-projected angular change in magnetic field direction between the source region and that containing the relativistic plasma. The relativistic rotation measure (Kennett & Melrose 1998),

$$\mathrm{RRM} = 3\times 10^4 L_{\rm pc}\langle n_r \gamma_{\rm min} B^2 \sin^2\theta\rangle \ \mathrm{rad/m^3}, \tag{3}$$

depends upon the pair density n_r, the path length $L_{\rm pc}$, measured in parsecs, and the minimum Lorentz factor of the pairs $\gamma_{\rm min}$. The linear polarization is $\sqrt{Q^2+U^2}$, and U is this times $\sin\psi$. Note that the linearly polarized component of synchrotron radiation is proportional to Stokes Q only, whereas the relativistic plasma converts between Stokes U and V. The observed degree of circular polarization then requires $\mathrm{RRM} \approx 14\xi/(m_l \sin\psi)$ rad/m^3. Bower et al. (1999a) report an observational limit $m_l < 0.001$. If this reflects the degree of linearly polarized emission incident upon the pair-dominated region, one requires $\mathrm{RRM} > 1.4\times 10^4\,\xi$ rad/m^3 in order to explain the circular polarization. It is possible, however, that depolarization of the (presumed) linear polarization occurs after the partial conversion to circular polarization, in which case m_l is higher and the corresponding limit on RRM is lower.

If linearly polarized radiation is incident upon a region containing an admixture of relativistic plasma and cold plasma, the ellipticity of the natural modes is then determined by the ratio $\lambda^3\mathrm{RRM_m}/\lambda^2\mathrm{RM_m}$, where RM is the rotation measure and the subscript m denotes values in the region containing the mixture. The highest degree of circular polarization that can result in a homogeneous medium is then

$$m_c = m_l \sin\psi \frac{\lambda \mathrm{RRM}_m}{\mathrm{RM}_m}. \tag{4}$$

This is only achieved provided $\lambda^2\mathrm{RM}_m \gtrsim 1$. In this case, the requirement on RRM_m is identical to that for a pair-dominated plasma. However, if $\lambda^2\mathrm{RM}_m \gg 1$ circular depolarization occurs because of rapid changes in sign with frequency.

Measurements of the circular polarization at other frequencies are required to determine the viability of circular repolarization models.

Finally we consider the effect of scintillation-induced circular polarization (Macquart & Melrose 1999). To exhibit this effect the source must be sufficiently small to undergo scintillation, and rotation measure fluctuations must be present in the scattering medium. The former is likely since Sgr A* is believed to exhibit variability in the total intensity due to interstellar scintillation (ISS) (e.g. Zhao et al. 1993). The RM fluctuations may arise from the region near the accretion disk (Melia 1994 and Bower et al. 1999a), or from further out in the Galactic Center region (e.g. Nicholls & Gray 1992, Yusef-Zadeh, et al. 1997). The mean scintillation-induced circular polarization tends to zero only over a time interval large compared to the timescale of variability of the circular polarization. The rotation measure gradient required to produce the circular polarization depends upon the variability timescale, which is related to the intrinsic size of the scintillating source. The timescale can influence the expected spectral dependence of the circular polarization. Further observations on the variability of the circular polarization are required to test the viability of this model and constrain the value of any possible rotation measure gradient.

5. Conclusion

We confirm the detection by Bower et al. (1999b) of circular polarization from the Galactic Center source, SgrA*. We note that our detection is from a different telescope and uses completely separate calibration and reduction strategy. Although clearly present, it is

difficult to identify the origin of the circular polarization in Sgr A*. Measurements of the circular polarization over at least a decade in frequency are needed to test the viability of these models, particularly those due to synchrotron emission and circular repolarization. Measurements of any possible variability would best constrain the role of scintillation in producing the circular polarization.

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Date	I	V	m_{V}	RMS	σ_{V}
	(mJy)	(mJy)	(%)	(mJy)	(mJy)
27 March 1996	616	-2.7	-0.42	0.24	0.22
31 March 1997	721	-2.6	-0.35	0.37	0.28
1 March 1999	581	-2.0	-0.34	0.10	0.10

Table 1: Detections of circular polarization for Sgr A* at 4.8 GHz